PALAEOCURRENT DIRECTIONS IN OTWAY GROUP SEDIMENTS, OTWAY RANGES, SOUTHEASTERN AUSTRALIA

By G. J. Medwell*

Abstract: Along the eastern coastline of the Otway Ranges, southern Victoria, Lower Cretaceous arkoses and mudstones of dominantly braided fluviatile origin contain five common primary structures of directional significance. These are filled channel-forms, planar and trough cross-bedding in arkose units, ripple mark, longitudinal erosion hollows and oriented cylindrical concretions. They have been used to derive a palaeogeographic reconstruction for Zone C (Albian) times in this part of the Otway Basin, showing drainage from north and south to join a central river system flowing westerly between Lorne and Cape Patton. The westerly-flowing trend has not previously been demonstrated.

Deposits of black coal are most likely to be found in the central area of the Ranges which was topographically the lowest part of the drainage basin.

INTRODUCTION

Douglas (1971, 1977) has discussed the Mesozoic and Tertiary setting of the Ranges. They are one of four outcrops of Lower Cretaceous sediments which lie en echelon in the latitudinal 'Great Valley of Victoria'. This is a major intracratonic rift system associated with the breakup of the Antarctic-Australian continent, beginning in the Jurassic and completed by the late Palaeocene (Boeuf & Doust 1975, Falvey 1974, Griffiths 1971).

The Otway Ranges consist of Lower Cretaceous braided fluviatile, paludal and lacustrine sediments, and constitute a High marginal to the Tertiary Otway Basin of south-west Victoria.

The main structural features of the Ranges (Fig. 2) were described by Medwell (1971), based on reconnaissance mapping of dips and strikes and a compilation of the work of several authors. The Ranges comprise a broad north-east trending anticline, possibly axially faulted, which plunges north-east into the Torquay Embayment and south-west into Bass Strait. An associated syncline, complicated by faulting and minor folding occurs on the southeastern side of the anticline. There are many monoclines, the largest of which are the Skenes Creek Monocline and the Devils Elbow Monocline. These two throw down in opposite directions from the elevated central part of the Ranges, which is thought to be essentially a flatlying and block-faulted area (Fig. 11).

Inland the Ranges are rugged and difficult of access, with poor exposures limited to tracks and creek beds. Good exposures are restricted to the shore platforms between Moonlight Head and Eastern View.

A survey has been made of part of this coastline, from Cape Otway to Eastern View, along most of the eastern flank of the Otway Ranges dome. Primary sedimentary structures which indicate palaeocurrent directions were recorded, and the sedimentation pattern inferred. The lack of detailed stratigraphic knowledge and the incomplete cover of the exposed section should however be noted.

DIRECTIONAL STRUCTURES

1. Filled Channel-forms (Allen 1968, Reineck & Singh 1973)

Small scour-and-fill structures almost always contain a dominantly mudstone lithology. Hence they occupy topographic lows on shore platforms, have a characteristic lensoid shape and show distinctive internal features (Pl. 7). More-or-less planar thin mudstones interbedded with arkose are rarer, and indicate channel-ways of the braided stream environment.

The commonly-found mudstone lenses have erosional bases which are sharply curved and cut into cross-stratified arkose. Maximum thickness is about 2-4 m, most being about 1-2 m. They frequently taper out over a distance of 10 to 100 m to meet the planar or undulose bedding surfaces of adjacent arkose beds.

The usual fill material is a sedimentary breccia of darker grey mudstone clasts in a grey mudstone matrix

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FIG. 1—Locality Map and Block Diagram of the Otway Ranges. Looking north-west from Cape Otway (foreground) towards Colac. Based on contours from Colac 1:250,000 Sheet, Mines Dept. Victoria, 1973.

(e.g. Boggaley Creek). Other fills are laminites of sandstone and mudstone (Grassy Creek), thinly-bedded sand and mud lenses (Skenes Creek), sandstone thinly bedded parallel to the scour base (Addis Bay), and massive mudstone.

The lenses represent cutoffs and abandoned channels in a braided fluvial system of deposition, filled with overbank fines and bank-collapse material during waning flood stage and low stage deposition.

In palaeocurrent analysis, the scoured channels were found to be the directional structures showing least dispersion at all localities where they are abundant, and thus the most reliable estimator of current direction. They are given code A — the innermost position — in the circle diagrams used below.

2. Cross-bedding

Most arkose beds and some mudstones show well developed internal cross-bedding of planar or trough types. On each shore platform 10-20 readings of maximum foreset inclination in arkose beds more than 0.5 m thick were easily obtained. Traces of cross-bedding planes are usually clearly visible as darker lines on sections of exposed beds, and are readily excavated where weathering is advanced. The dark lines are concentrations of coalified plant remains. Sometimes cross-bedding planes are marked by small rounded clasts of mudstone, by iron oxide cement, and rarely by calcite of secondary origin. Some show ferruginisation due to weathering.

Cross-bedding marked by coal fragments: Three oriented slabs with abundant coal fragments lying on foreset planes were sampled at Skenes Creek. The orientations of fragment long axes were plotted, as percentages in 30-degree sectors, to determine if preferred orientation of linear coal could be demonstrated. Bimodal distribution (with and normal to current) became evident in the plots (Fig. 3), though not always readily apparent in hand specimen. One correction for tectonic tilt was made stereographically, ignoring regional plunge and initial dip. Results agreed well with the overall palaeocurrent vector mean for the locality.

This technique may be useful in the hinterland of the Ranges where good exposures are limited and statistically reliable palaeocurrent directions are more difficult to obtain.

Results must be interpreted with caution. The coal fragments are oriented by local currents sweeping over the top and down the avalanche face of braid bars of various types. Sometimes the avalanche face is skewed at a large angle across the stream bed (see Allen 1968) and the local current is strongly divergent from the overall downstream direction. Further, currents may flow along and not down the avalanche face, as when generating 'reverse cross-bedded cross-beds' (Williams 1971). Provided these limitations are recognised, oriented coal may be a useful current indicator.

Examples of other cross-bedding: Cross-bedding may be marked by rounded clasts of mudstone and sandstone. Examples of sigmoidal cross-stratification showing this occur in a road cutting on the Barham road at the west end of Noel St., Apollo Bay, and in sea cliffs south-west of the mouth of the Elliott River.

In sea cliffs under Cinema Point Lookout, intersections of bedding planes with cross-bedding topsets and upper foresets of the bed below are preserved in the internal structure of a spheroidal calcified concretion approx. 10 cm in diameter. A similar structure can be seen at Artillery Rocks, in a large concretion forming a pedestal rock 1 m high (Pl. 8).

Ferruginised cross-beds are exposed in road cuttings north of the mouth of Skenes Creek on the Forrest road.

Interpretation of cross-bedding: Initially, cross-bedding which did not accord with the range of current directions and the mean palaeocurrent vector for a locality was regarded as probable hindsets. Later an alternative explanation became evident.

The shore platforms commonly expose strike sections (b-c sedimentary plane of Allen 1968) up to 100 m long, in bedding which dips seawards at low to moderate angle. The cross-stratification exposed is undulose and often in restricted zones, not permeating the full thickness of the bed. At intervals, vertical-sided gulches cut in the shore platform by marine erosion expose dip sections (a-c plane). Here the cross-stratification is seen to be generally pervasive, with traces usually sigmoidal or flexed. This relationship is illustrated in Fig. 4, which sketches beds at the Grey River mouth. It is also evident at the Mt. Defiance seawall, where almost vertical beds show strike sections in the shore platform and dip sections in the road cutting above.

The structures are interpreted as internal cross-stratification due to migratory sandwaves, with sinusoidal crests over a length of several metres in plan and about 1-2 m high. They resemble the delta-cross-stratification of Allen (1963) but occur at larger scale. Modern aeolian analogues have been observed at Sandy Point, Waratah Bay. Bed forms of a size capable of producing such internal features are well known from several modern river systems (see for example, Coleman 1969, Harms & Fahnestock 1965, Williams 1971).

As a palaeocurrent direction indicator, the cross-bedding can be measured in two ways:

• by estimating the trend of the troughs and/or crests evident in the strike sections. Multiple dip readings taken on a curved stratification surface are plotted

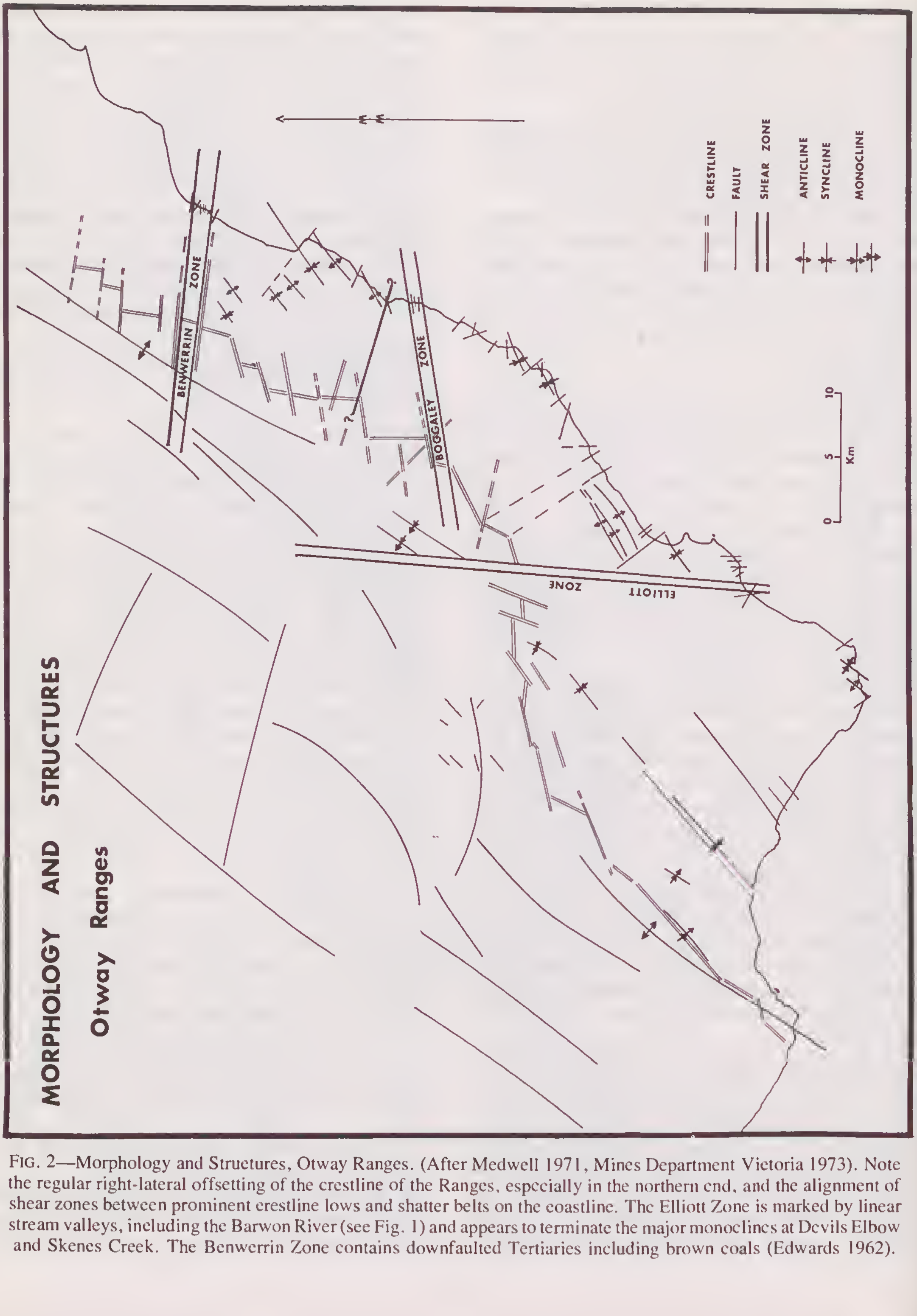


FIG. 2—Morphology and Structures, Otway Ranges. (After Medwell 1971, Mines Department Victoria 1973). Note the regular right-lateral offsetting of the crestline of the Ranges, especially in the northern end, and the alignment of shear zones between prominent crestline lows and shatter belts on the coastline. The Elliott Zone is marked by linear stream valleys, including the Barwon River (see Fig. 1) and appears to terminate the major monoclines at Devils Elbow and Skenes Creek. The Benwerrin Zone contains downfaulted Tertiaries including brown coals (Edwards 1962).

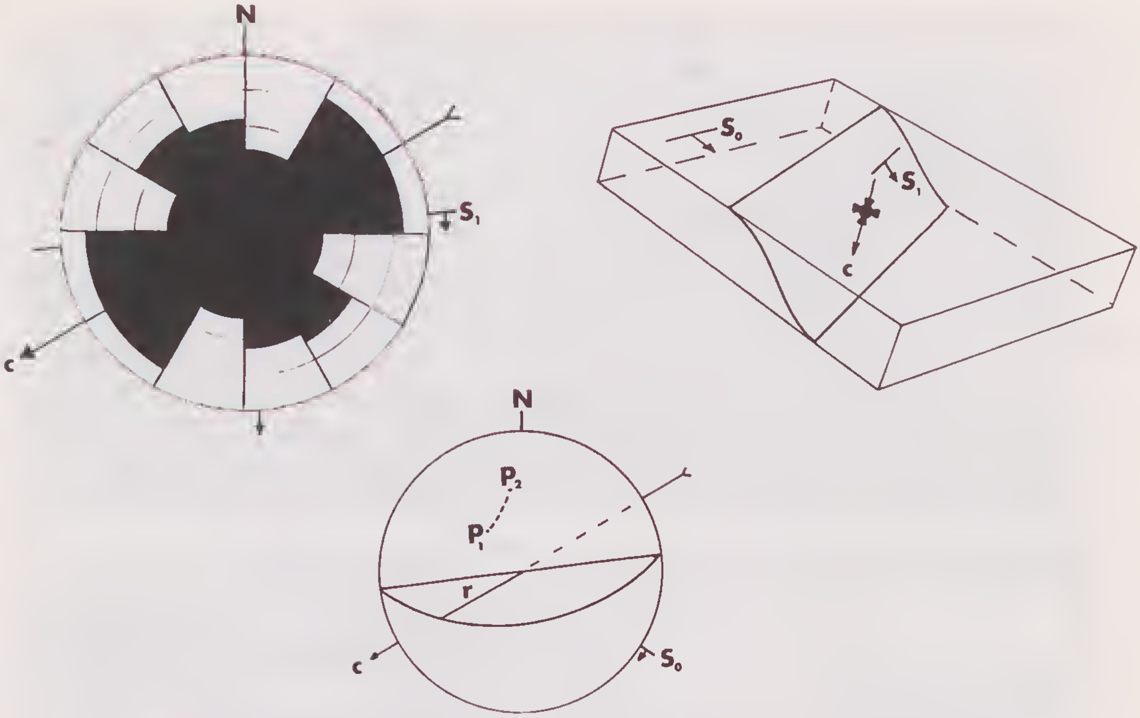


FIG. 3—Interpretation of Oriented Coal Fragments on Foresets. Rosette from oriented slab shows bimodal preferred orientation. Strongest mode is most likely along-current. Scale interval 5%. S_0 Bedding. S_1 Foresets. C Current direction angled across bedform. P_1 Pole of foresets. P_2 Pole of foresets after correction for dip of S_0, corresponding plane shown, r Rake of C in plane of S_1.

stereographically, and the trend of the structure obtained from a π or β diagram.

- by measuring the maximum dip of the planar surfaces exposed in the dip sections. These must be expected to show considerable dispersion at any locality.

Cross-bedding current directions are shown as Structure Code B below (Fig. 5).

3. Small-Scale Ripple Mark

Small-scale ripple mark (Structure C) is found only in thin-bedded facies of restricted distribution.

Asymmetric current ripples (X = 5 cm, h = 1 cm) tend to occur in fine-grained sediments wherever thin-bedded sequences are well developed. Such sequences are predominantly mudstones, but may contain arkose bands up to 2 m thick. They are not common, having been found only at Cape Otway Lighthouse, south-west of Parker River mouth, between Elliott River and Storm Point, near Cape Patton, in Addis Bay, at 'Flatrock' south-west of Wye River (Picnic Point), at The Brothers near Lorne, and at Point Grey.

The thin-bedded sequences thus occur in occasional belts, commonly 500 to 1000 m in strike width and about 100 m in thickness. They are probably natural levee or overbank deposits formed along major channels during mainly low stage periods, and preserved in part during succeeding floods, possibly by channel avulsion.

The tops of some of the more sandy strata are ripple-marked, and yield a current sense. Where constant direction of asymmetry is observed, a current direction can be obtained for fine material.

Ripple mark is also found occasionally in the thin beds filling the erosional channel-forms described above (Structure A).

4. 'Crests and Troughs'

Larger-scale undulations resembling ripple mark were noted at the base of thick arkose beds which overlie the mudstone fill of several small scours. Best examples are in the roadcutting at the Cape Patton Lookout, and in the Skenes Creek north-east shore platform near the end of the camping reserve (Pl. 5). In each case λ = 1 m, and h = 0.3-1 m.

These crests and troughs were first thought to be current megaripples (Allen 1968) but were later found to lie mostly parallel to the estimated local current direction. They are possibly too large and regular for load casts. True load casts are generally absent from the sections examined, and bedding surfaces between arkose and mudstone are planar or gently undulose.

The crests and troughs are tentatively regarded as

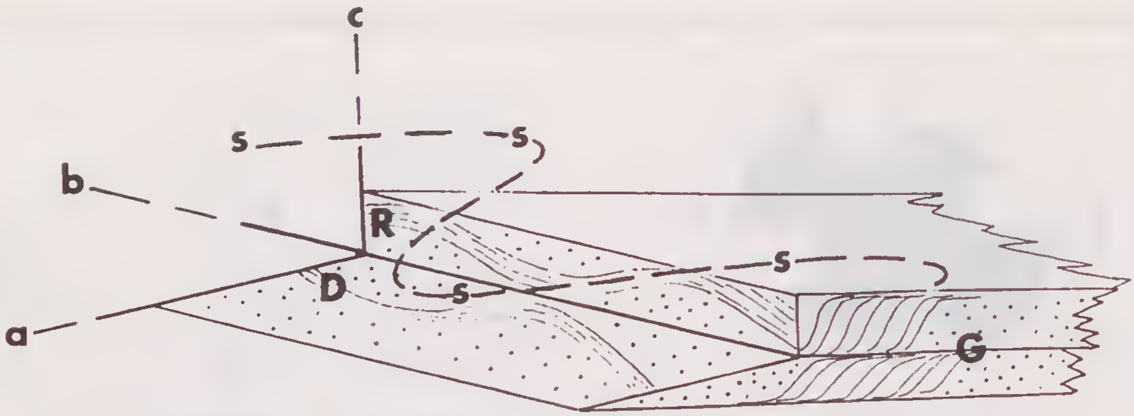


FIG. 4—Interpretation of Crossbedding in Arkose, Grey River Mouth, Otway Coast. a,b,c = Sedimentary axes (Allen, 1968). a = Current, b = Right bank, c = Vertical, R = Rampart, D =Depression of shore platform, G = Gulch, -s-s-s-s-s = Sinuous crest of bedform.

DESCRIPTION OF PLATES 5-8

PLATE 5

Primary Directional Structures in Otway Group Sediments.

Upper and Centre: Oriented cylindrical concretions, Cleary River mouth, south-west side. Concretions lie in plane of bedding. *Upper:* Small-scale. For section, see Plate 6B. *Centre:* Large-scale. *Lower:* 'Crests and troughs', Skenes Creek mouth, north-east side. Arkose moulds of longitudinal (down-current) grooves, scoured by a succeeding flood in the soft mudstone fill of an erosion channel. For scale, note hammer in centre foreground.

PLATE 6

Internal Structures in Small-Scale, Homogeneous Concretions of Calcified Arkose, Otway Coast. Actual size.

Left — Photographs showing apparent homogeneous nature of sectioned concretions.

Right — Corresponding X-radiation prints. X-radiopaque laminations become visible (mica, secondary oxides of iron, etc.). After Hamblin (1962).

A. Small-scale planar bedding, probably mica layers.

B. Homogeneous arkose, rim of secondary iron oxides.

C. Small-scale crossbedding internally, rim of iron oxides.

D. Homogeneous arkose.

PLATE 7

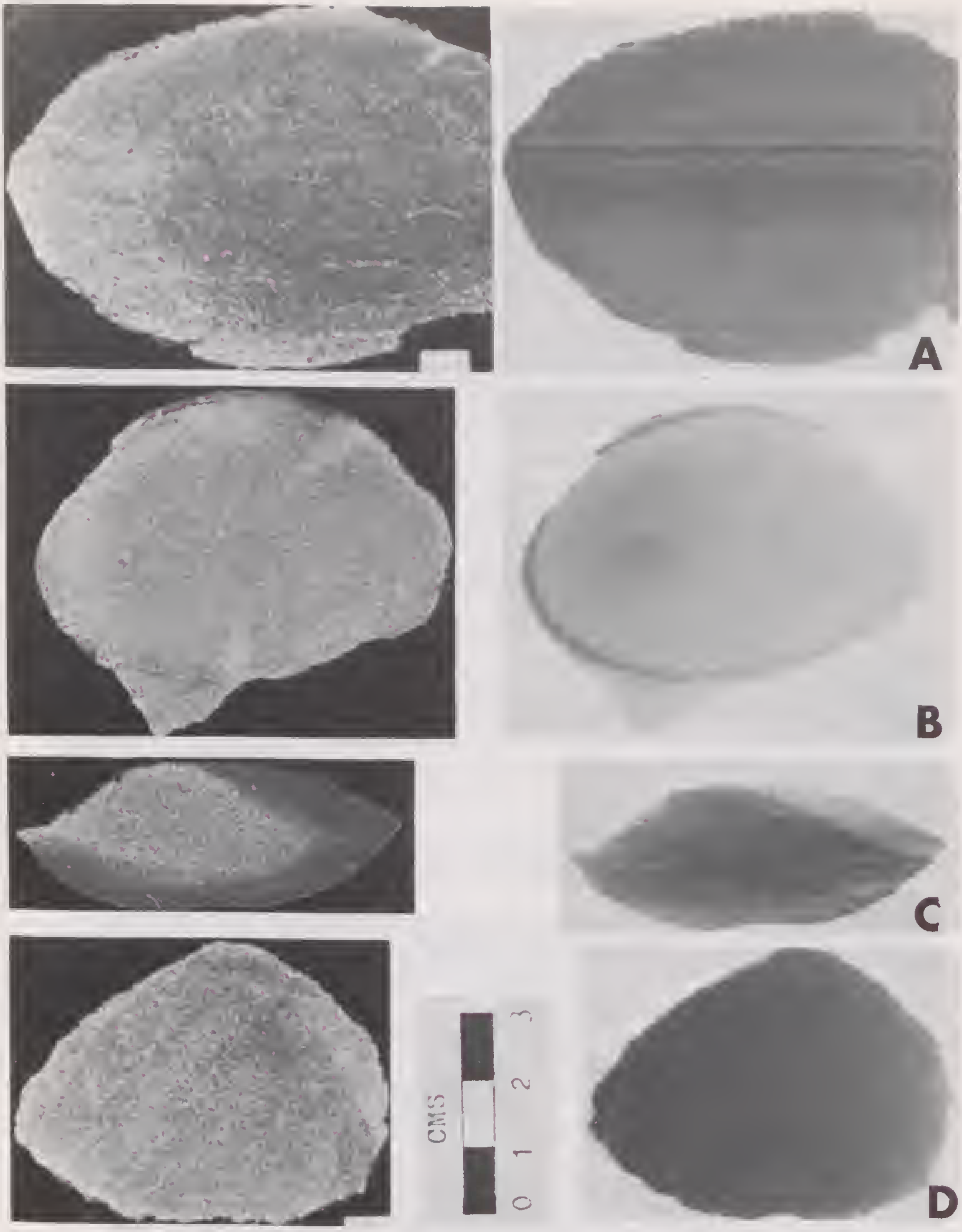
Filled Channel-Form, Wild Dog Creek. Near north-east end of shore platform, opposite 'The Falls'. Small channel-form with two lobes in the erosional base. Lobes yield slightly different current directions, indicating channel migration during scour. Fill is sedimentary breccia (angular mudstone clasts in a mudstone matrix). Minor fault transects scour, offsetting planar base of overlying arkose beds by approx. 30 cm. Note hammer on boulder along fault trace. Maximum thickness of scour, approx. 2 m.

PLATE 8

Concretions in Otway Group Arkoses.

Upper: Sandball type. Smythes Creek Quarry, east wall.

Lower: Calcified arkose type. Pedestal rock, Artillery Rocks, showing bedding dipping south-east (right) and crossbedding dipping flatly north-east (left).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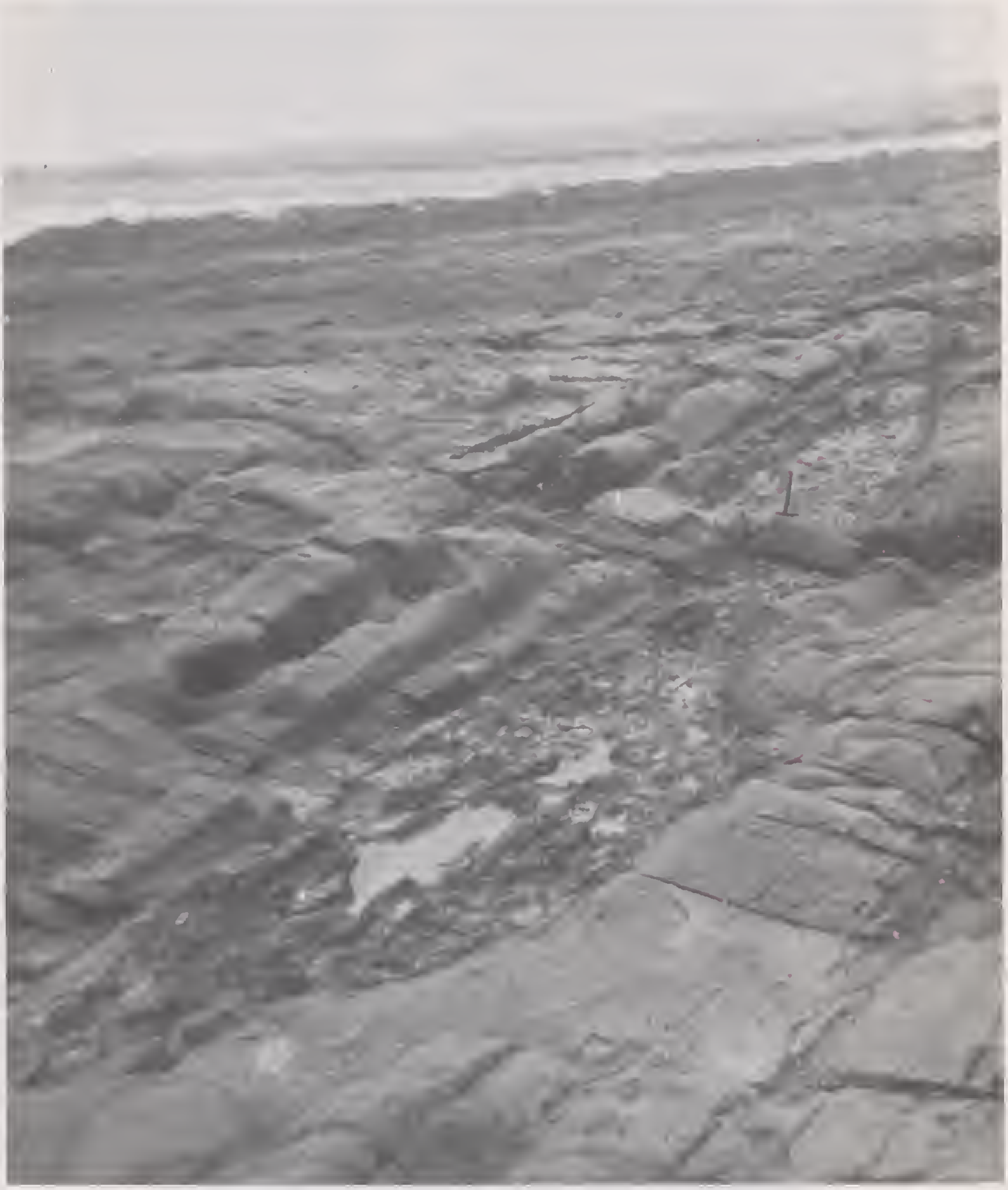

longitudinal scour structures, formed in the soft muds of abandoned-channel fill during early overbank period of the next flood stage, and preserved by advance of braid bars during full flood and subsequent waning. Rapid rise of stage without prolonged erosion is indicated.

Because of their uncertain origin they were treated initially as D // and D ⊥ — meaning Structure Code D, parallel to current if scours and normal to current if megaripple. D // is usually more in agreement with the locality vector mean.

5. Cylindrical Concretions

Calcareous concretions are abundant in arkose beds, and on weathering and marine erosion stand out in relief on the cliffs and shore platforms (Pl. 8). Two types are present — calcified arkose type (probably secondary in origin) and 'sand-ball' or pod type, which consist of coarse sand, heavy minerals and pyrite (Stirling 1901), often within a ferruginised shell. At Mt. Defiance the latter show a fining-up sequence of spheres, becoming progressively smaller in a succession of arkose beds. Some concretions are cylindrical with diameters of 20-100 cm and more, and lengths of 0.5 to 2 or 3 m. Others are spheroidal, up to 50 cm diameter.

The cylinders tend to occur in groups or sets and commonly are aligned either normal or parallel to the estimated current direction (Pl. 5). In some places, dual sets are seen (both normal and parallel to current) and occasionally individual concretions may be bent twice at right angles into a U-shape. They are called Structure Code G (G // and G ⊥) in the analysis since it is usually not possible to know independently whether they are locally parallel or normal to current.

Possibly they are due to rolling of sand-rich pods during flood stage, forming cylindrical zones when entrained in channel-bar deposits, which are then favoured as a locus of deposition for circulating solutions during diagenesis, lithification and weathering.

Sets of unusually large cylinders occur south-west from the mouth of the Elliott River (Pl. 5). A few are found on most shore platforms.

P. Conaghan (1975, pers. comm.) has suggested that some may be in fact calcified logs, the decomposing woody tissue setting up chemical gradients in the lithifying sediments which promote local calcification. A search has been made for internal tree ring structures, by X-radiation and thin section, but these are generally absent (Pl. 6).

J. Douglas (1975, pers. comm.) suggests that they may be of algal origin, having noted similar structures in the Grampians sandstones (Early Devonian or older), formed before trees existed.

Treatment of Structures Code D & G: Each example of Structures Code D or G was first plotted as four equivalent possible current source directions. Then using other structures which are more current-sensitive to indicate the likely source quadrant, one of the four values was subjectively selected for statistical treatment and inclusion in the grouped data for the locality.

6. Lineations

Linear features on bedding planes are sometimes useful. These include entrained coalified logs and preferred orientation of coal fragments (Structure Code E).

Coalified logs are rare except north of Lorne at Cathedral Rock. Here several were found in the shore platform, ranging up to 1 m in length.

Preferred orientation of linear coal fragments on bedding planes and cross-stratification planes was demonstrated to be potentially useful, but only one example was in fact included (see limitations, above).

7. Small-scale Structures

Small-scale foresets (Structure Code F) were found in overbank thin-bedded sequences and in the fill of channel forms, mostly in the thin sandstones. They were measured at Addis Bay and Point Grey and included in the overall data for current direction determination at those localities.

PALAEOCURRENT DIRECTION MEASUREMENT

Methods

The most consistent indicator of current directions proved to be the scoured channel forms, filled with mudstone, arkose bands and sedimentary breccia. Several occur on most shore platforms, especially between Lorne and Cape Patton, where eight or ten per km of coastline may be found.

Five or six readings of the attitude of the erosional contact at the scour base were made, together with that of the bedding nearby, and plotted on the stereographic projection.

The poles of each dip measurement fall on a girdle on the projection, which defines the section-plane normal to the axis of the channel-form. The pole to this plane is the axis of the channel, and after correction for tectonic tilt indicates the local current vector as an azimuth and plunge angle.

Foresets in a-b or a-c planes (Allen 1968) were measured as often as encountered, together with foreset troughs (see Fig. 4), ripple mark, longitudinal erosion scours, and linear features such as entrained logs and cylindrical concretions.

Because individual primary structures are not abundant, every available structure was measured in the field. Structures occurring in groups (e.g. foresets) were measured at 2 or 3 places and the arithmetic mean used.

Sampling

No formal pre-designed sampling plan was employed. However, an hierarchical grouping structure was developed, consisting of

(i) *Exposures* — usually about 100 m of shore platform, sea cliff and adjacent road cuttings, identified by a fieldbook number.

(ii) *Localities* — groups of several adjacent exposures, showing consistent trends, containing about 10 measurements, and identified by a locality name.

(iii) *Sectors* — for computing moving-average trends, the coastline was divided into 5 km sectors, measured north-east from Cape Otway and identified by the letters A-M. Each sector contained up to 3 or 4 localities.

(iv) *Areas* — three Areas, or groups of many Localities and Sectors were outlined, defining discrete parts of the former basin of deposition.

(v) *Region* — the whole coast sampled, from Cape Otway to Eastern View.

Statistical Procedure

Data was analysed using the procedures advocated by High and Picard (1971). These are set out in their Fig. 6, and involve

- Correction for tectonic tilt and plunge
- Demonstration that directional data for different structures are statistically equivalent and capable of being grouped (Kolmogorov-Smirnov test)
- Use of the Tukey Chi-square statistic to demonstrate nonrandom orientation from the grouped data at each locality

The Rayleigh statistic, as advocated by Curray (1956) was also computed, and found generally more sensitive. Where a preferred unimodal distribution was not evident, Tanner's (1955) procedure for polymodal distributions was followed

- Calculation of measures of central tendency and dispersion, namely vector resultant, mean for grouped data, vector magnitude, variance and standard deviation. Where mean and vector resultant differ significantly due to choice of origin, data was transformed linearly (+180°) and the mean and variance recalculated
- Moving-average analysis of the region divided into 5 km sectors
- Map representation, compass diagram and circular histogram construction; identification of sub-areas within the basin
- Reconstruction of palaeogeographic trends.

Selection and Grouping of Measurements at Outcrop Level

Scours, troughs and crests, foresets, and linear features were first plotted on the stereographic projection (Wulff net) and tilt due to dip of bedding removed. Minor secondary tilt due to plunge of nearby folds was ignored as statistically insignificant. Following Ramsay (1961, Fig. 5, p. 89) and Potter and Pettijohn (1963, p. 261), the angular error in azimuth from neglecting plunge is less than 5° in the following cases: plunge $\langle$ 10° : S_0 dips up to 63°; plunge $\langle$ 20° : S_0 dips up to 35°; plunge $\langle$ 30° : S_0 dips up to 42°. Plunges in the Otways appear to be shallow ($\langle$ 10°) and dips are rarely over 45°.

Using the reduced data, a circular diagram (Fig. 5) was constructed showing palaeocurrent directions for every type of structure present.

The most significant vectorial structures were placed in the centre; other scalar and possibly ambiguous structures were placed towards the periphery. Then the range of readings to be accepted was marked in the eye of the diagram.

The diagrams thus gave a visual subjective estimate of the possible range of current directions, and readings from scalar structures were selected accordingly to be grouped with vectorial data (scours and foresets) as input to the computer. Nearly always the selected reading was found to *parallel* the observed attitude of the scalar structure (e.g. logs parallel to current); much more rarely were normals to observed attitudes included.

Grouping of Outcrops into Localities, and Naming Localities

By comparing the ranges of acceptable readings for adjacent outcrops, groupings of 3-4 outcrops with similar trends into localities were made. These are the units used in the summary (Table 1), assembled in sequence north-east from Cape Otway. Each is a shore platform (or part of one) and has little other geological significance. Localities may therefore be grouped or regrouped as desired. The localities used were selected to contain about 10 measurements each, as suggested by High and Picard (1971, p. 34) and Potter and Pettijohn (1963, p. 256).

Locality names in Table 1 were usually chosen from the mouth of the nearest named river (indicating on which side, north-east or south-west): thus 'Grey River S.P. SW' means 'Grey River shore platform, south-west from river mouth'.

Hence localities are groups of adjacent outcrops, from 2 to 4 or 5 in number, which show consistent palaeocurrent directional trends, and which contain approx. 10 measurements. They have been grouped from inspection of the circular outcrop-group diagrams

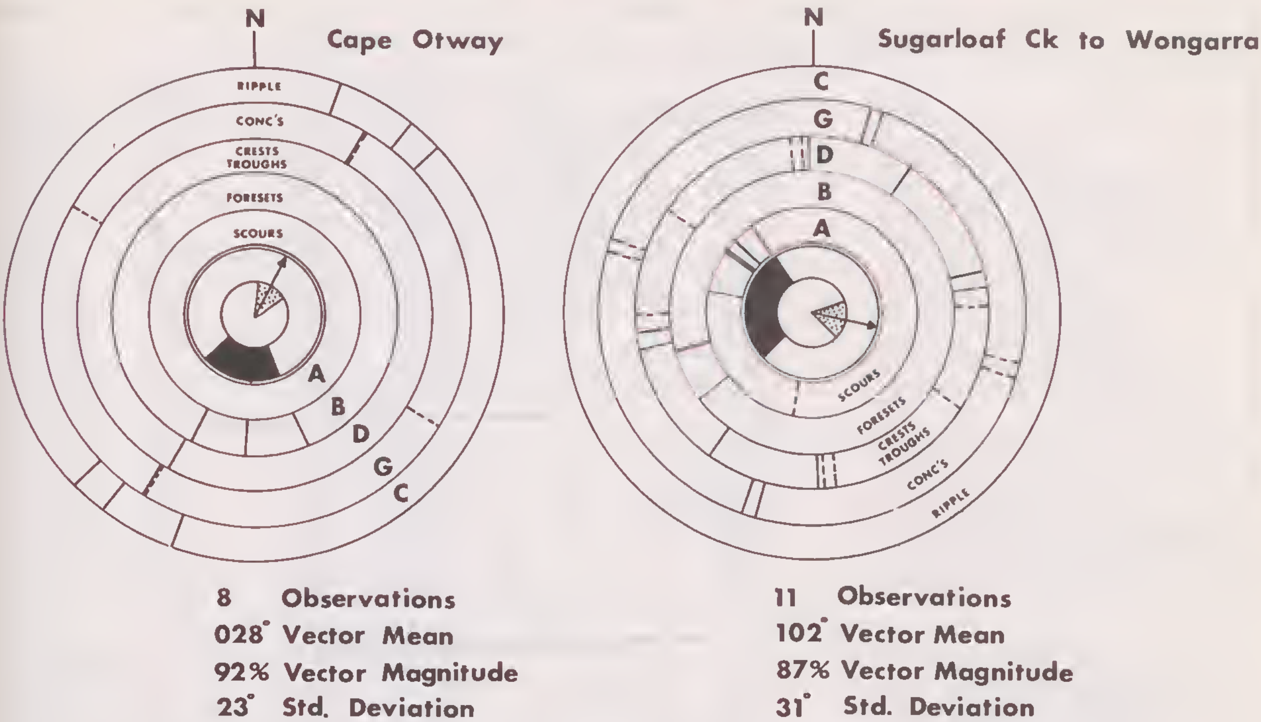

FIG. 5—Two Examples of the Circular Diagrams used in the Selection of Directional Structures. Central Part: Current Vector Mean; arc subtends one standard deviation each side. Range of likely current sources (shown in black). Peripheral Part: Directional structures measured at this locality.

as having essentially similar overall ranges of palaeocurrent source directions.

Computer Processing

A computer program was written in ICL 1900 Fortran to increase flexibility of ordering of data groups and to ensure mathematical accuracy. The computer calculated for each locality (and then for data grouped in various manners) a variety of statistics:

- Vector mean and significance using the Tukey Chi-square test (High & Picard, 1971 p. 33).
- Vector mean and vector magnitude ('consistency ratio') after the method of Reiche (1938).
- Mean, variance and standard deviation for classed (grouped) data (Koch & Link 1970).
- Probability that the calculated value of x_2 is not the product of random orientations, using tables of Dixon and Massey (1951, p. 308).
- Rayleigh test of significance (Curray 1956, p. 175 and Fig. 4).

Since grouping of localities would tend to produce polymodal distributions, the data needed for the compass diagrams and rose diagrams of the Tanner procedure were produced, namely mean number of observations per interval with associated standard deviation and variance. Results appear in the format of a work-sheet, allowing manual checking, following High and Picard (1971 p. 34, after Harrison, 1957). At the end of each set of localities there is a summary by class interval of all observations submitted, which can be used to repeat the computations for sectors, sub-areas and for the region as a whole. A summary table listing all results is produced at end-of-run (Tables 1 to 4).

ANALYSIS OF PALAEOCURRENT RESULTS

Recognition of Areas

Inspection of the compass diagram (Fig. 7) representing the polymodal distribution for the whole region reveals three modes. The three sub-areas are respectively Cape Otway to Point Sturt (near Wye River), Point Sturt to Point Grey (Lorne), and north-east of Lorne. Each shows a well-developed preferred orientation when all palaeocurrent data are plotted as a circular histogram, indicating sources to the south, east and north-west this is consistent with accepted ideas on the regional structure of the basin of deposition (Wopfner & Douglas, 1971).

Detailed Palaeocurrent Trends

For a more precise estimate of current trends, vector mean (V.M.) and vector strength (L½) are shown in Table I as computed at locality level, and are plotted on Figs. 8 and 9. Readings have been grouped into 30°

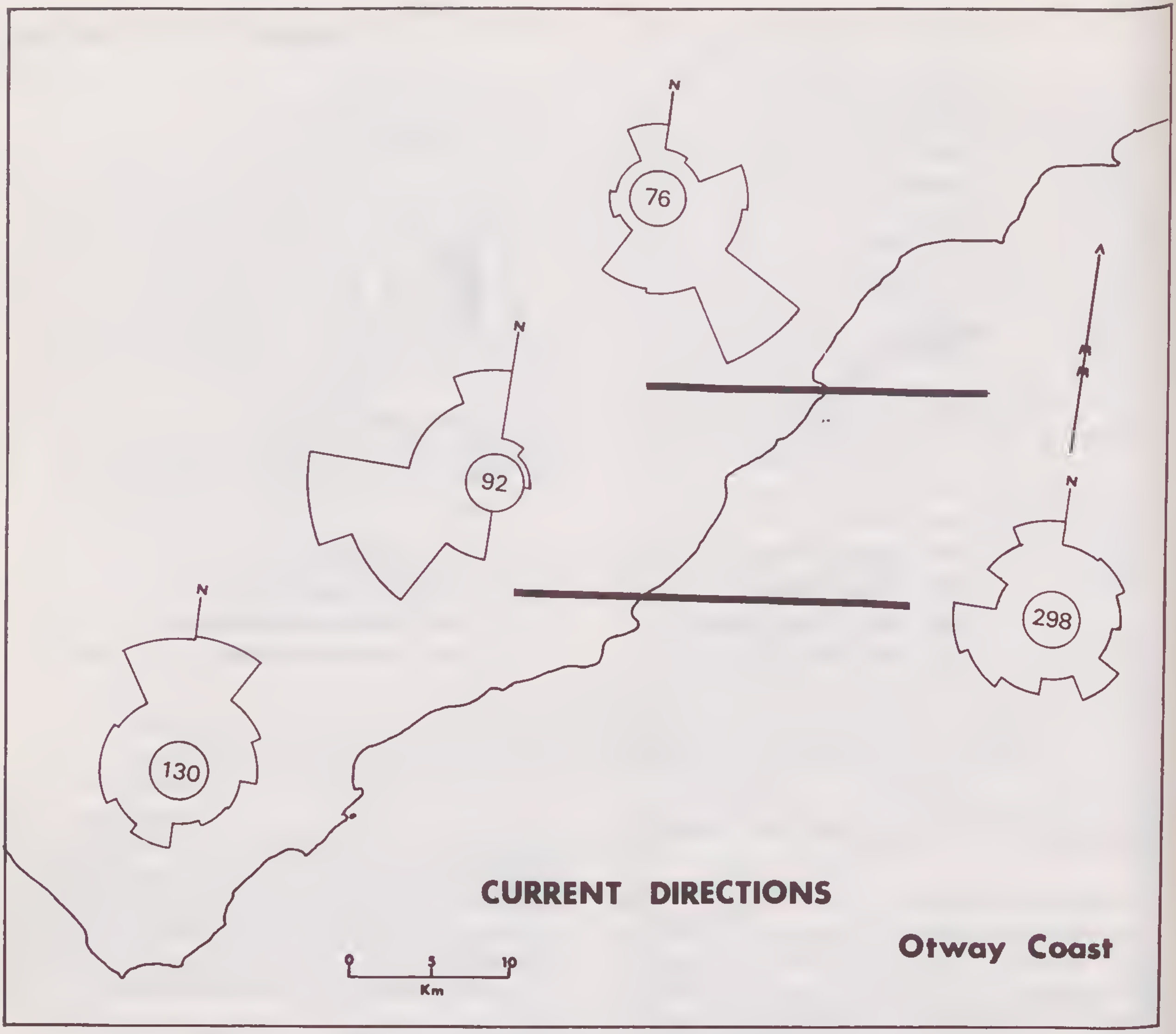

FIG. 6—Current Directions, Otway Coast: Roses.

classes as suggested by High and Picard (1971, p. 35). Inspection of each vector mean direction in Fig. 8 shows a general uniformity of overall trend within each area, but considerable local variance, and occasional gross divergence. The gross divergencies are all near major faults or monoclines (Elliott River coastline, Skenes Creek Monocline, Carisbrook Creek and Reedy Creek).

Dispersion around the vector mean is shown in Fig. 9 by vector magnitude (L% — Curray 1956). The vector magnitude shows appreciably lower values in the central area, compared with northern and southern areas where it commonly exceeds 85%. This decline in vector strength reflects a greater dispersion of values around the mean (Potter & Pettijohn 1963), presumably due to the lower gradients of the central part of the basin. The dispersion was noticed in the field before any knowledge of the palaeocurrent directions was available, from the larger range of current source directions.

At Lorne, the change in source direction from north-west (northern area) to east (central area) is abrupt. It occurs at Point Grey where a fault zone is evident in the shore platform, trending north-west, and a small synclinal structure recorded by A. B. Edwards (unpub. field notes) is exposed at low tide. The syncline is probably caused by drag on the fault zone.

In contrast, the change in source direction from east to south at Point Sturt is more gradual, occurring over about 5 km of coastline in sector H.

TABLE 1.
CURRENT SOURCE DIRECTIONS. LOCALITIES — CAPE OTWAY TO EASTERN VIEW.

VECTOR RESULTANT	VECTOR MAGNIT.%	SIGNIFICANCE TUKEY	RAYLEIGH	NO. OBS	MEAN	VARIANCE	STD.DEV'N	LOC.NO.
208.3	92.9	0.995	0.0023678	7	207.9	557	23.60	745 CAPE OTWAY
77.4	86.2	0.995	0.0000301	14	77.1	1034	32.15	746 PARKER RIVER SW
325.1	81.5	0.995	0.0001781	13	268.8	13592	116.59	748-52 ELLIOTT R. COASTLINE
285.0	100.0	0.950	0.0497871	3	285.0	0	0.00	753 ELLIOTT RIVER NE (MUDSTONES)
126.2	89.4	0.995	0.0003410	10	126.0	810	28.46	754-758 STORM POINT
166.7	83.6	0.995	0.0004553	11	165.0	1260	35.50	734-9 SWELL PT TO CAPE MARENGO
156.2	59.9	-0.900	0.2385889	4	157.5	3825	61.85	747 CUTTING, NOEL ST. APOLLO BAY
113.8	54.5	0.950	0.0282861	12	115.0	3655	60.45	741-2 WILD DOG CREEK
24.9	97.0	0.995	0.0002109	9	25.0	225	15.00	740 SKENES CREEK SW
174.4	88.4	0.990	0.0092107	6	175.0	960	30.98	733 & 732 SKENES CREEK NE
282.8	87.0	0.995	0.0002425	11	282.3	982	31.33	716B WONGARA TO SUGARLOAF
218.3	60.0	0.950	0.0390068	9	205.0	4050	63.64	715-6A SUGARLOAF-CARISBROOK CK.
191.6	83.5	0.995	0.009452	10	192.0	1290	35.92	711-2 CAPE PATTON-GREY R.
215.1	65.2	0.990	0.0093533	11	205.9	3289	57.35	706,713 GREY R. TO ADDIS BAY NE
76.5	52.3	0.900	0.0646200	10	93.0	4640	68.12	710,717-8 KENNETT R. TO PICNIC PT
103.7	57.0	0.950	0.0389136	10	108.0	3890	62.37	719-21 PICNIC PT TO PT STURT
137.3	88.1	0.995	0.0000189	14	137.1	895	29.92	722 WYE R. TO BOGGALEY CK.
93.8	59.6	0.990	0.0099130	13	98.1	3323	57.65	725-8 BOGGALEY CK.
142.9	90.8	0.950	0.0369187	4	142.5	825	28.72	729-31 GODFREYS CK-ARTILL. ROCKS
116.6	43.2	-0.900	0.1547372	10	126.0	5210	72.18	767-9 JAMIESON R. TO MT DEFIANCE
81.2	84.6	0.995	0.0032404	8	82.5	1221	34.95	770-2 CUMBERLAND R - SHEOAK CK.
69.9	74.9	0.995	0.0006826	13	72.7	2019	44.94	765-6 TEDDYS LOOKOUT S.P.
65.1	79.5	0.995	0.0018041	10	66.0	1610	40.12	701 POINT GREY SW
328.3	87.0	0.995	0.0005187	10	291.0	10160	100.80	773,763,764 POINT GREY, LORNE
320.1	90.2	0.995	0.0000001	20	267.0	11975	109.43	774-6 STONY CK TO REEDY CK.
179.6	78.3	0.995	0.0006334	12	187.5	2148	46.34	777-8 REEDY CK - CATHEDRAL ROCK
264.9	79.3	0.995	0.0009827	11	246.8	3436	58.62	760,761 BIG HILL CREEK, NE & SW
55.6	72.4	0.995	0.0006488	14	83.6	7398	86.01	779-80 CINEMA PT - BALL HOUSE SP
345.0	82.9	0.995	0.0020492	9	268.3	16450	128.26	762,779 GRASSY CREEK

TABLE 2.
CURRENT SOURCE DIRECTIONS. SECTORS.

VECTOR RESULTANT	VECTOR MAGNIT.%	SIGNIFICANCE TUKEY	RAYLEIGH	NUMBER OBS.	MEAN	VARIANCE	STD.DEV'N	LOC.NO.
109.6	43.9	0.975	0.0173767	21	120.7	4826	69.47	SECTOR A CAPE OTWAY
337.4	17.5	-0.900	0.4526653	26	215.8	12079	109.91	SECTOR C ELLIOT R.
160.0	69.4	0.995	0.0004500	16	155.6	2486	49.86	SECTOR D MARENGO
90.0	37.7	0.975	0.0215819	27	98.3	5146	71.74	SECTOR E WILD DOG
282.8	87.0	0.995	0.0002425	11	282.3	982	31.33	SECTOR F SUGARLOAF
202.0	70.5	0.995	0.0000793	19	198.2	2489	49.89	SECTOR G CAPE PATTON
173.0	35.3	0.900	0.0735559	21	166.4	5533	74.38	SECTOR H KENNETT
126.8	72.4	0.995	0.0000035	24	125.0	2243	47.37	SECTOR I WYE NE
111.2	54.8	0.995	0.0003054	27	115.0	3738	61.14	SECTOR J JAMIESON
71.5	78.4	0.995	0.0000000	31	73.1	1616	40.20	SECTOR K CUMBERLAND
306.4	47.5	0.995	0.0000760	42	250.0	10050	100.25	SECTOR L LORNE
349.5	36.4	0.975	0.0111216	34	185.3	15476	124.40	SECTOR M CINEMA PT

TABLE 3.
CURRENT SOURCE DIRECTIONS. MOVING AVERAGES OF ADJACENT SECTORS.

VECTOR RESULTANT	VECTOR MAGNIT.%	SIGNIFICANCE TUKEY	RAYLEIGH	NUMBER OBS.	MEAN	VARIANCE	STD.DEV'N	LOC.NO.
109.6	43.9	0.975	0.0173767	21	120.7	4826	69.47	SECTOR AB
337.4	17.5	-0.900	0.4526653	26	215.8	12079	109.91	SECTOR BC
169.0	17.3	-0.900	0.2944790	41	196.5	8818	93.90	SECTOR CD
130.0	41.2	0.995	0.0007886	42	121.4	4838	69.56	SECTOR DE
4.6	10.2	-0.900	0.6614004	40	161.2	12286	110.84	SECTOR EF
234.3	58.9	0.995	0.0000305	30	229.0	3583	59.86	SECTOR FG
191.8	50.5	0.995	0.0000374	40	181.5	4244	65.14	SECTOR GH
140.2	51.4	0.995	0.0000069	45	144.3	4125	64.22	SECTOR HI
119.7	62.5	0.995	0.0000000	51	119.7	3001	54.79	SECTOR IJ
86.3	63.6	0.995	0.0000000	58	92.6	3001	54.78	SECTOR JK
19.6	28.4	0.995	0.0027238	73	174.9	14151	118.96	SECTOR KL
322.6	39.7	0.995	0.0000063	76	221.1	13352	115.55	SECTOR LM

TABLE 4.
CURRENT SOURCE DIRECTIONS. AREAS AND REGION SUMMARIES.

Number Obs.	Mean	Variance (Transformed)	Std. Dev'n	Locality
298	148.2	5544	74.46	Summary: Region
130	159.7	6034	77.68	Summary: Cape Otway to Pt. Sturt
92	101.1	3110	55.77	Summary: Pt. Sturt to Pt. Grey
76	185.5	3437	58.63	Summary: North-east of Lorne

Palaeogeographic Reconstruction

At sector level, moving averages of vector means and vector strengths were computed to smooth local variations and distribute current symbols evenly across the map without regard to outcrop control. These are shown in Fig. 10. Vector strengths as expected are considerably lower.

The tripartite nature of current trends along the coastline is again seen, but emphasis is given to the radial pattern of current directions in the central area, converging into the region west of Wye River.

The east-to-west trend of currents in the central sector may reflect the general slope of the rift valley of southern Australia in Albian times (I. McPhee 1975, pers. comm.), including the Strzelecki Basin (Hocking 1972) and the Bass Basin. Alternatively, the Mornington Peninsula — King Island ridge may have been topographically high during the Albian, dividing the rift valley into separate basins of deposition in the Early Cretaceous. Lower Cretaceous sediments at Inverloch are regarded as estuarine (A. Link 1975, pers. comm.) rather than fluviatile so that the latter suggestion seems more likely at present.

Fig. 10 suggests the pattern of sedimentation for the Otway Coast. North-south ridges, probably of low relief, divide piedmont slopes into broad open valleys with braided channel systems, flowing inwards and then westerly along the rift valley. Overbank facies are scarce, suggesting largely emphemeral streams such as those of eastern Central Australia today.

Areas of swamp and lake deposition are indicated by thin-bedded sequences such as at Skenes Creek, and by some thick mudstones, such as at Cape Otway and Elliott River.

Economic Significance

The palaeocurrent trends have considerable economic significance. Mesozoic rocks contain Victoria's only major deposit of bituminous black steaming coal, at Wonthaggi (Knight 1975, Edwards and others 1944). The Otway Ranges were investigated for further deposits in 1900 (Strling 1901), by means of several drill holes near Apollo Bay and Skenes Creek, where 12-inch (0.3 m) coal seams were being worked along the valley of Wild Dog Creek within the Skenes Creek Monocline belt.

With a better understanding of original deposition and later tectonic modification, the search for a black coal field in the Otways might be resumed. Exploration in the low-lying regions of the basin offers best hope of locating coal swamps, and as shown in Fig. 10, this means initially in the Ranges to the west of Wye River. Basin analysis should be extended to the rest of the Ranges, as sedimentation trends inland from the coast are unknown.

The area of interest is triangular and lies between Cape Patton, Point Grey, and Forrest. Reconnaissance mapping (Edwards 1962, Medwell 1971) suggests that the central part of this region is a plateau dipping flatly north-east (10°–20°), which is ringed by structurally disturbed belts — the Devils Elbow Monocline, Lorne Syncline, Mt. Defiance Anticline and fault, Kennett and Patton Synclines, and Skenes Creek Monocline. It is also transected by many small faults and two major fault zones (Fig. 11).

High Regional Variance

When total readings from all localities are accumulated and grouped into classes, to compute a grand vector mean and a regional variance (Table 4), the resulting variance (5544) is unusually high. Potter and Pettijohn (1963) quote 4000-6000 as being characteristic of fluviatile deposits generally. Casshyap and Qidwai (1971) obtained figures of 2045 and 4178 for formations from environments dominated by braided streams and meandering streams respectively. McDonnell (1974) obtained a total variance of 2049 for the Gosford Group (Triassic) of the Sydney Basin, commenting that this reflected measurements on pi-cross-bedded sandstones identified as channel bars in a 'low sinuosity low-braiding' fluvial system.

When total variance is computed for each area (northern, central, southern) and transformed data is used where necessary to obviate the effect of choice of origin, respective figures of 3437, 3110 and 6034 are obtained (Table 4). These are still somewhat higher than might be expected in a braided stream environment. They may reflect the combining of readings

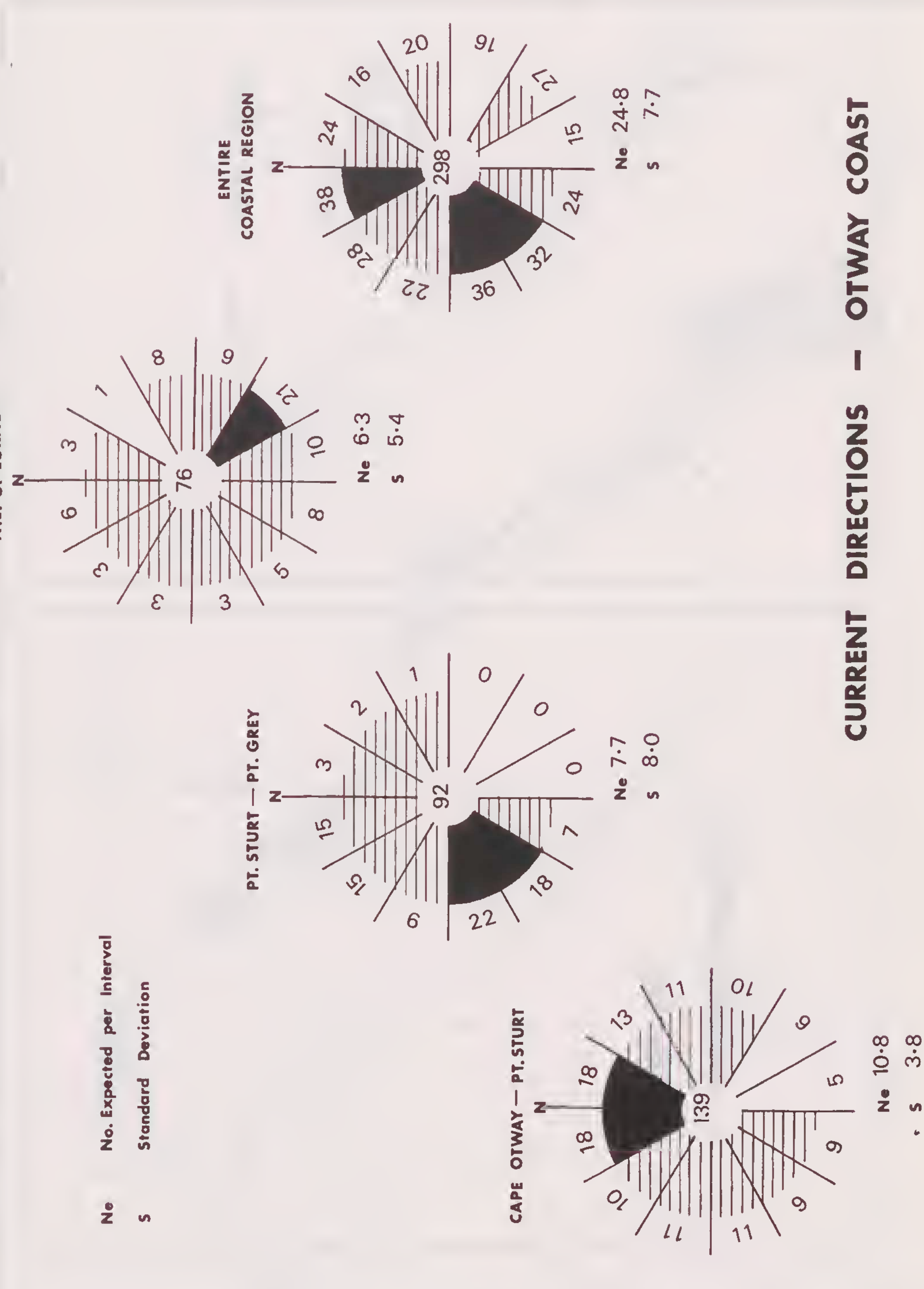

FIG. 7—Current Directions, Otway Coast: Compass Diagrams.

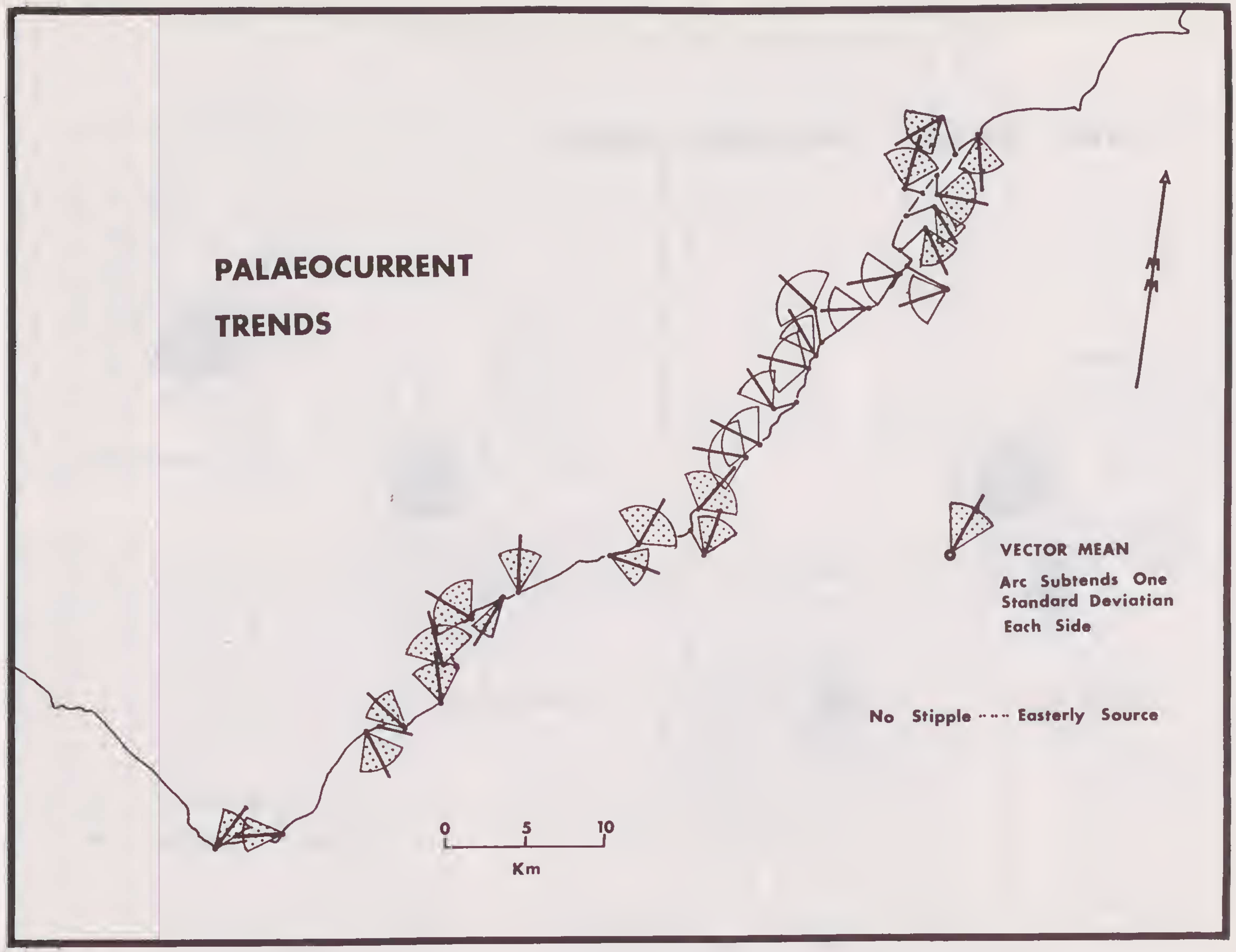

FIG. 8—Palaeocurrent Trends at Coastal Localities Sampled.

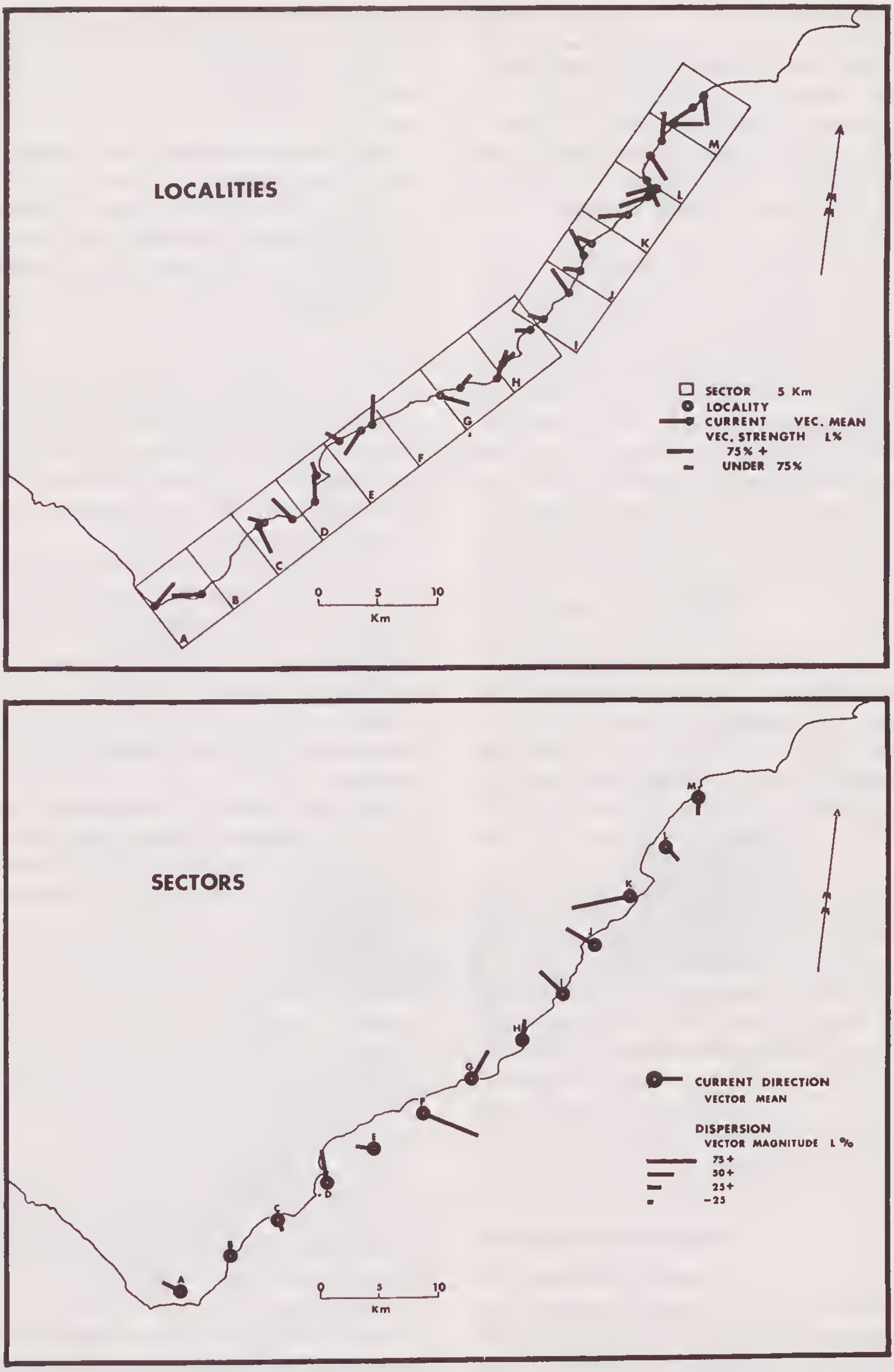

FIG. 9—Palaeocurrent Trends by Locality and Sector.

from five sets of different structures. Certainly they reflect the generally marked angular difference between source directions inferred from cross-bedding and from filled channel-forms at most localities.

Four localities were noted where gross divergence from the inferred regional trends occurs. These are the localities termed Elliott River Coastline, Skenes Creek south-west to Wild Dog Creek, Carisbrook Creek south-west, and Reedy Creek.

Each is near a major fault or monocline whose effects are not adequately known. Elliott River Coastline lies south-west from the mouth of the Elliott River, where an abrupt change in strike occurs and faulting is inferred ('Elliott Zone', Fig. 11).

At Wild Dog Creek, the beds in the shore platform increase in dip southwesterly (from 46° to near vertical) over a strike length of about 1 km at the foot of the Skenes Creek Monocline. Carisbrook Creek and Reedy Creek are each the site of faults inferred by Edwards (1962) from linear valleys and dislocation of beds in the shore platforms. At Reedy Creek a basin structure interpreted as dragged bedding on a major fault is visible.

If the discrepancies are not of later tectonic origin, they represent flow directions in the basin of deposition generally opposite to the overall trends and suggest local topographic highs, as marked on Fig. 10 by dashed lines. These may have been intermittently formed by syndepositional tectonism with north to south trends, resulting in defeat of streams and the periodic formation of swamps, lakes and coal measures.

A third possible explanation might stem from inability to distinguish separate stratigraphic horizons along the coast. The anomalous localities may be younger deposits (Zone D) preserved in local grabens. If so, they suggest by their northerly source-indication that the axis of the basin (Central Area of this study) migrated south through the Early Cretaceous. This would accord both with Kenley's suggestion (in Wopfner & Douglas 1971, Fig. 21.11) that the early (Zone B) 'axis of greatest shaliness' was located nearer the northern margin of the rift valley, and the observation here presented, that the basin axis was south of Lorne by Zone C time.

SUMMARY

The coastline of the Otway Ranges, between Cape Otway and Eastern View, exposes 65 km of Lower Cretaceous sediments, thought to be essentially of the same stratigraphic position (Zone C of Douglas 1971, that is, Albian) because of the domed structure of the Ranges.

Five directional primary structures were found to be abundant. These are filled channel-forms ('scours'). foresets in arkose units, crests and troughs aligned downcurrent by penecontemporaneous erosion, ripple mark, and alignment of cylindrical (pod-shaped) concretions.

Filled channel-forms are most abundant along the central coast between Lorne and Cape Patton. They contain easily-erodible mudstone, sedimentary breccia and thinly-bedded sandstones and hence are topographically low. The axis of the structure (plotted stereographically) was used, and commonly showed small dispersion about the local mean palaeocurrent trend.

The maximum inclination of foreset beds in thick arkose units showed considerable dispersion. This structure is best measured in the a-c sedimentary plane, which is usually in the vertical wall of gulches in the shore platforms. The shore platforms commonly expose the a-b plane, in which the foresets are seen to be sinuous and non-penetrative.

Cross-bedding is often marked by coalified plant remains, which are oriented normal and parallel to strictly local current directions down or along the avalanche face of the bedform.

Ripple mark was restricted to the mudstones of thin-bedded sequences, which occur only at a limited number of outcrops. These represent the levee and overbank suites of palaeochannel deposits and are not abundant.

Crests and troughs of longitudinal (with-current) hollows in mudstones filling channel-forms were also used. These were grouped with other undulose structures in arkose beds, whose orientation (with-or across-current) is less certain.

Finally, use was made of oriented calcareous concretions. Two types of concretion occur in these rocks — calcified arkose spheres and cylinders, and 'sandballs' which may be spherical or pod-shaped.

When cylindrical they are commonly oriented approximately down-current, and were probably rolled up by flood-stage currents and entrained in braid bars during waning stage deposition.

These structures were shown to have statistically equivalent distributions and were grouped to give a minimum of ten observations per locality, wherever possible. The grouped data was computer processed providing tables from which Figs. 6-10 were constructed. These show current direction and dispersion (as vector mean and vector magnitude L %) for localities and sectors (5 km of coastline), and moving averages for adjacent sectors.

A palaeogeographic reconstruction was made for Zone C times, showing well-defined southerly-flowing streams in the northern Ranges, turning to

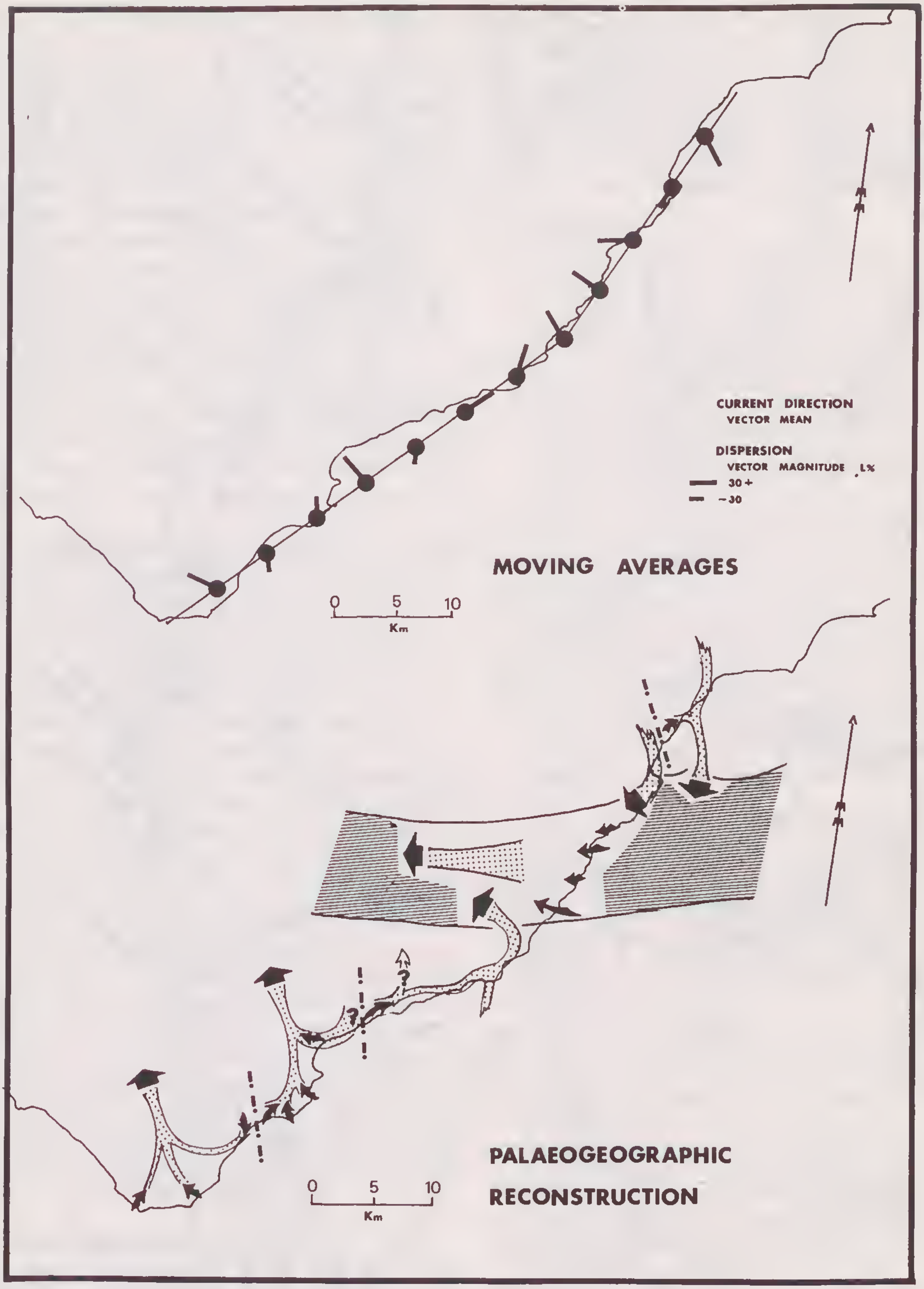

FIG. 10—Moving Averages and Palaeogeographic Reconstruction.

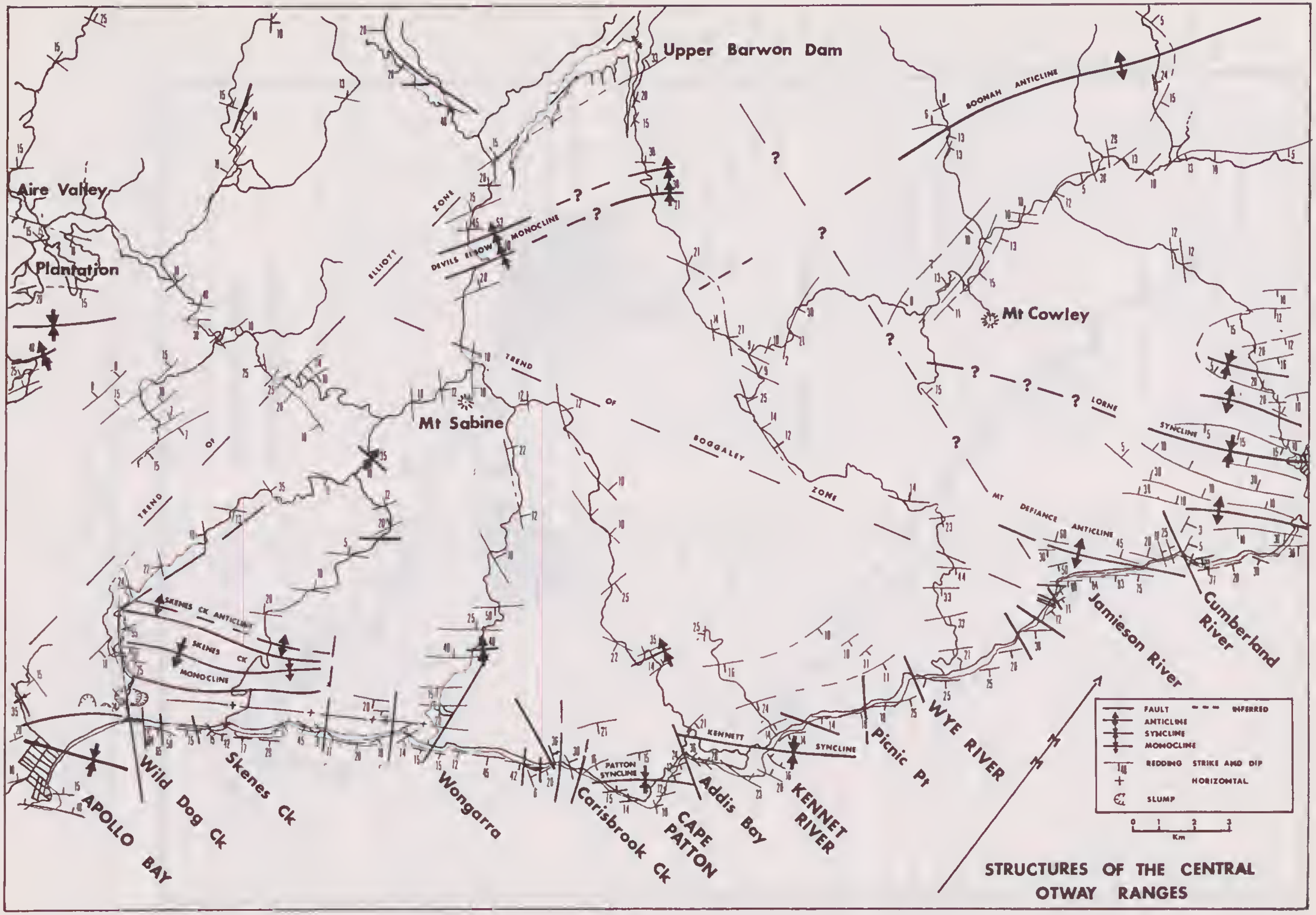

FIG. 11—Structures of the Central Otway Ranges.

westerly-flowing in the region south of Lorne and then to northerly-flowing south of Kennett River.

These trends generally confirm previous ideas on the basin sedimentation pattern derived from oil bores (see Kenley in Wopfner & Douglas 1971). However, the westerly-flowing trend in the central area has not previously been noted.

An eastern source area for the central part of the ancient Otway Basin may imply that the Mornington Peninsular-King Island ridge was a high in Albian times, and hence probably throughout the Early Cretaceous. It therefore separated the Otway Basin from the Strzelecki Basin during the early stages, continuing to do so until the present. It may thus be a feature of considerable permanence, astride the rift valley.

Alternatively, the region of westerly-flowing streams may indicate that the whole of the Early Cretaceous rift valley, from Gippsland to South Australia, drained westerly. Probable estuarine conditions of sedimentation at Inverloch would seem to preclude this.

Some of the palaeocurrent directions obtained imply that north to south trending divides may have existed between adjacent drainage basins. They suggest an environment of shallow wide valleys with braided streams in which high flow regimes were rarely attained (contrast the Hawkesbury Sandstone environment described by Conaghan & Jones 1975). In these valleys the distribution of lakes and swamps was irregular, with no apparent control which can be identified as yet. The central part of the Otway Ranges is the most likely area to contain black coal seams of economic significance. This is an elevated flat-lying region surrounded by major faults, folds and monoclines, and transected by many faults.

The palaeocurrent directions show a high variance which is considerably in excess of published data for other deposits of braided streams. The factors causing this include great variability in cross-bedding measurements, grouping of different primary structures, tripartite division of source regions, low gradients in the central area, possible local tectonic disturbance, and perhaps the inclusion of unrecognised beds from higher stratigraphic positions. In the region of the Skenes Creek Monocline, almost 1000 m of sediments dip steeply towards the sea, so that the stratigraphic position of the present coast is uncertain.

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